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CARBON FOOTPRINTING

Need for relevant timescales when crediting temporary carbon storage

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Abstract
Purpose Earth faces an urgent need for climate change mitigation, and carbon storage is discussed as an option. Approaches for assessing the benefit of temporary carbon storage in relation to carbon footprinting exist, but many are based on a 100-year accounting period, disregarding impacts after this time. The aim of this paper is to assess the consequences of using such approaches that disregard the long timescale on which complete removal of atmospheric CO_2 occurs. Based on these findings, an assessment is made on what are relevant timescales to consider when including the value of temporary carbon storage in carbon footprinting.
Methods Implications of using a 100-year accounting period is evaluated via a literature review study of the global carbon cycle, as well as by analysing the crediting approaches that are exemplified by the PAS 2050 scheme for crediting temporary carbon storage.
Results and discussion The global carbon cycle shows timescales of thousands of years for the transport of carbon from the atmosphere to pools beyond the near-surface layers of the Earth, from where it will not readily be re-emitted as a response to change in near-surface conditions. Compared to such timescales, the use of the 100-year accounting period appears hard to justify. We illustrate how the use of the 100-year accounting period can cause long-term global warming impacts to be hidden by short-term storage solutions that may not offer real long-term climate change mitigation. Obtaining long-term climatic benefits is considered to require storage of carbon for at least thousand years. However, it has been proposed that there may exist tipping points for the atmospheric CO_2 concentration beyond which irreversible climate changes occur. To reduce the risk of passing such tipping points, fast mitigation of the rise in atmospheric greenhouse gas concentration is required and in this perspective, shorter storage times may still provide climatic benefits.
Conclusions Both short- and long-term perspectives should be considered when crediting temporary carbon storage, addressing both acute effects on the climate and the long-term climate change. It is however essential to distinguish between short- and long-term mitigation potential by treating them separately and avoid that short-term mitigation is used to counterbalance long-term climate change impacts from burning of fossil fuels.

Keywords Climate change mitigation · Carbon cycle · Carbon storage crediting · Accounting period for global warming potential · Carbon footprints

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1 Introduction

Mitigation of man-made global warming and climate change is high on the agenda in international politics. Critical characteristics of climate change impacts are both the long-term effects of a changed climate and the more acute risk of passing climatic tipping points, beyond which

we may experience dramatic, adverse and possibly irreversible changes in the climate, either on a regional or global scale (Meehl et al. 2007).

The Intergovernmental Panel on Climate Change (IPCC) has in the Fourth Assessment Report estimated that an increase in the global atmospheric average temperature exceeding 2–3 °C is potentially dangerous (Hansen et al. 2008), and the European Union has adopted a goal of keeping the temperature rise due to anthropogenic emissions below 2 °C compared to preindustrial temperatures (Council of the European Union 2005). Some investigations even suggest that it may be necessary to reduce the atmospheric CO_2 concentration to a level below 350 ppm (Hansen et al. 2008), from the present level being 387 ppm (NOAA 2011). This is expected to keep the global atmospheric average temperature increase above pre-industrial level below 1 °C (Solomon et al. 2007).

The strong attention to the global warming issue has inspired an increasing focus on the embedded CO_2 emissions in products and systems as expressed in the carbon footprints that is now being used by many companies, NGO's and other institutions, with a potential to promote the principles of life cycle assessment (LCA) (Weidema et al. 2008).

In the carbon footprint context, the possibility of temporarily keeping carbon out of the atmosphere through its storage elsewhere is gaining interest, as an option for climate change mitigation. Suggested options for carbon storage count various methods from carbon capture and storage (CCS) over carbon sequestration in forests to short-term storage in, e.g. man-made wooden products.

However, the issue of whether or not temporary carbon storage provides value for mitigating climate change is debated. Some argue that storage of carbon for a certain time can compensate cumulative climatic impacts of CO_2 emissions (e.g. Moura-Costa and Wilson 2000). Others counterargue that in a long-term perspective, temporary carbon storage does not give much benefit to climate change, and may even have a negative climatic impact, as it decreases some impacts while increasing others (e.g. Kirschbaum 2006; Meinshausen and Hare 2002). Others again claim, that there is a value in temporary carbon storage through its ability to reduce impacts of climate change in the short term and thus 'buy time' for more permanent solutions to be developed and implemented (e.g. Dornburg and Marland 2008; Fearnside 2008).

A central issue in the argumentation for crediting temporary carbon storage is the atmospheric lifetime of CO_2. This issue has been widely debated in the literature. In the discussions of climate change, the atmospheric lifetime of CO_2 is often considered determined by the equilibration of CO_2 between the atmosphere and the superficial parts of the ocean and terrestrial biosphere, disregarding the slower equilibria for removal processes further along the carbon cycle (Archer et al. 2009). This difference is explained by Archer and Brovkin (2008), as an issue of 'exchange rates' versus 'net removal rates'; while single CO_2 molecules in the atmosphere may exchange with the ocean or terrestrial biosphere over a timescale of a few years, timescales for net removal of CO_2 from the atmosphere are much longer. The atmospheric lifetime of anthropogenic CO_2 is given by Archer et al. (1997) as several hundreds of years for 70–80 % of the emission, and from several thousands to hundreds of thousands of years for the rest, as consequence of the naturally occurring removal mechanisms. This agrees rather well with the IPCC estimate, giving an atmospheric lifetime of 30 years for approximately half of a CO_2 emission, a few centuries for the next 30 % of the emission and many thousands of years for the last 20 % (Denman et al. 2007). Thus, it is insufficient to only consider the short equilibration time of CO_2, when the focus is on the long-term climate change mitigation. Several studies consider the longer timescales of the carbon cycle and the removal mechanisms behind them, e.g. Archer and Brovkin (2008), Siegenthaler and Sarmiento (1993), Des Marais (1997) and Bertaux et al. (2007). This is elaborated on in relation to Fig. 1, presented in Section 3.1.

In the assessment of climate change impacts from products a 100-year time horizon is often applied for calculating global warming potential (GWP) impacts for greenhouse gases, reflecting the time horizon that was adopted in the Kyoto Protocol (UNFCCC 1998). However, the choice of the 100-year time horizon in the Kyoto Protocol is not supported by scientific arguments, but rather believed to reflect the fact that this was the middle choice of the three GWP time horizons presented by the IPCC (Shine 2009). The issue of the atmospheric lifetime of CO_2 after an emission, and the importance of the choice of time horizon for determining global warming impacts of atmospheric CO_2 in LCA is also discussed in Müller-Wenk and Brandão (2010).

In crediting carbon storage, an accounting period is often used, based on an interpretation of the time horizon, as implying that impacts occurring after this time are not included (e.g. Moura-Costa 2002; Clift and Brandão 2008). Thus when temporarily storing carbon, some of the cumulative impact that would otherwise have occurred within the accounting period will move beyond it and be considered avoided.

Temporary carbon storage can be expressed in the environmental account or carbon footprint for a product or technology as negative CO_2 equivalents (CO_2e), as suggested in the British PAS 2050—a voluntary scheme specifying how to calculate embedded greenhouse gas emissions for goods and services, i.e. emissions occurring in the life cycle of the good or service (BSI 2008). The scheme includes a specification of how to credit temporary carbon storage in products. The PAS 2050 applies a 100-year accounting period and we use it in this study for illustrating the result of cutting off climate change impacts occurring after the 100-years accounting period. In the new edition of the PAS

2050 (BSI 2011), considering temporary carbon storage is optional and must be reported separately from the carbon footprint. However, the first version of the PAS 2050 is still a good example of results from applying a 100-year accounting period. Henceforth in this article, when referring to PAS 2050, it refers to the first edition (BSI 2008). The key aspects of the PAS 2050 are briefly outlined in Section 2.

Several other suggestions for crediting temporary carbon storage exist (see e.g. Brandão et al. 2012). Development of standards for carbon footprinting has also been undertaken by organisations such as World Business Council for Sustainable Development, World Resource Institute, International Organization for Standardization, as well as in initiatives under several national ministries (Finkbeiner 2009). In October 2010, an expert workshop on temporary carbon storage for use in LCA and carbon footprinting took place at the Joint Research Centre of the European Commission (Brandão and Levasseur 2011). However, no consensus has yet been reached on how to include the temporary carbon storage in LCA and carbon footprinting.

The aim of this paper is to analyse the relevance of different accounting periods when crediting the temporary storage of carbon in terms of saved carbon footprints and to discuss the consequences of current approaches using the 100-year accounting period in the light of the timescales of the global carbon cycle.

2 Methods

The ability of the PAS 2050 carbon storage crediting approach (BSI 2008) to ensure real climate change mitigation is investigated by analysing the long-term climate change consequences of a delay of emissions by 100 years. The influence of the accounting period on the credited GWP savings is assessed by varying the accounting period of the PAS 2050 from 2 to 1,000 years. Finally, an assessment is conducted to determine the adequate accounting period to apply for crediting temporary carbon storage when considering the transport times between the relevant compartments of the global carbon cycle.

2.1 The global carbon cycle

Based on a literature study, an overview model of stocks and timescales in the complete global carbon cycle is set up—see Fig. 1 (the study is shown in the "Electronic supplementary material", together with assumptions and a complete list of references).

2.2 Crediting of man-made carbon storage

In PAS 2050, the storage credit, expressed as CO_2e, is subtracted from the carbon footprint, i.e. the climate change impact from the rest of the product system (BSI 2008). Key requirements for the crediting are e.g. that the carbon stored in products must be of biogenic origin or in the form of CO_2 withdrawn from the atmosphere, it must be additionally stored as a result of human activity, meaning that the carbon would not have been stored had it not been for this project, and the storage has to occur during the 100-year accounting period, counting from the manufacture of the product (BSI 2008). However PAS 2050 applies a similar approach for delayed emissions of fossil CO_2 as well (BSI 2008).

Carbon storage credit for a product is calculated from the total amount of carbon stored in the product, by applying a weighting factor. The weighting factor depends on the duration of the storage and is calculated using Eq. (1) (BSI 2008).

$$\text{Weighting factor} = \frac{\sum_{j=1}^{100} x_j}{100} \tag{1}$$

where x_j is the share of the total storage which remains in any year j within the 100-year accounting period.

In cases where the full amount of carbon is stored for a shorter period between 2 and 25 years after manufacture of the product, followed by total release of the stored carbon, the following approximation applies, as suggested by Clift and Brandão (2008) and presented in the PAS 2050 (BSI 2008):

$$\text{Weighting factor}_{2-25} = \frac{0.76}{100} \cdot t_s \tag{2}$$

where t_s is the duration of the full storage in years after product formation, and 0.76/100, here termed the *GWP saving factor*, is a factor derived by Clift and Brandão (2008) which is further discussed in the next section.

2.3 Accounting period dependency of the PAS 2050 results

We calculate GWP saving factors as the one shown in Eq. (2) for different accounting periods, to illustrate the dependency on the choice of accounting period. This is done using the approach applied in the PAS 2050 approximation for short delay times. All equations from Clift and Brandão (2008) (see this reference for further explanations and derivations):

The decay function for CO_2 in the atmosphere $f(t)$ is as given by the IPCC:

$$f(t) = a_0 + \sum_{i=1}^{3} a_i \times \exp(-t/\tau_i) \tag{3}$$

where a_0, a_i and τ_i are specific coefficients and time constants for three removal processes (i=1, 2, 3) that are active in the IPCC decay function for CO_2 in the atmosphere, as reflected in the revised Bern carbon cycle model (see Forster et al. 2007).

The GWP saving factor multiplied with the time of storage is defined as the fractional saving of radiative forcing from CO_2 due to the carbon storage:

$$\text{GWP saving factor} \times t_s = I(t_s)/I_T \tag{4}$$

where $I(t_s)$ denotes saved GWP within the accounting period of T years due to a t_s years delay of emissions, and I_T represents the GWP during the accounting period of T years, without the storage.

I_T is based on the atmospheric CO_2 decay function (3) and is given as:

$$I_T = a_0 \times T + \sum_{i=1}^{3} a_i \times \tau_i \times [1 - \exp(-T/\tau_i)] \tag{5}$$

$I(t_s)$ is likewise based on the atmospheric CO_2 decay function (3), but only during the period from T–t_s to T, and can for short delay times be approximated by replacing $f(T)$ with the tangent to $f(T)$ at time T. The resulting expression for $I(t_s)$ is:

$$I(t_s) = t_s \times (f(T) - f'(\mathrm{T}) \times t_s/2) \tag{6a}$$

where $f(T)$ is the decay function for CO_2 in the atmosphere, during the accounting period of T years, and $f'(T)$ is the derivative of $f(T)$ with respect to the accounting period T.

Introducing (3) in (6a), it can be derived that for storage times t_s up to 25 years, the second term of (6a) becomes insignificant and the following approximation is reasonable:

$$I(t_s) \sim f(T) \cdot t_s \tag{6b}$$

Introducing (6b) and (5) into (4), the GWP saving factor can be determined for complete storage times t_s of 2–25 years, for any accounting period T:

$$\text{GWP saving factor}_{2-25} = \frac{\alpha_0 + \sum_{i=1}^{3} \alpha_i \times \exp(-T/\tau_i)}{\alpha_0 \times T + \sum_{i=1}^{3} \alpha_i \times \tau_i \times [1 - \exp(-T/\tau_i)]} \tag{7}$$

In Clift and Brandão (2008), the GWP saving factor is calculated for an accounting period of 100 years. In this paper, GWP saving factors have been calculated for accounting periods from 2 to 1,000 years, to show how results depends on the length of the accounting period.

3 Results and discussion

3.1 The global carbon cycle

The overview model resulting from the literature review study of the global carbon cycle is shown in Fig. 1.

As can be seen from Fig. 1, transport of carbon (in the form of CO_2) from the atmosphere down the carbon cycle involves various mechanisms with very different timescales, which makes modelling of the overall removal of CO_2 from the atmosphere rather complex. It thus takes relatively short time for the CO_2 concentration in the atmosphere to equilibrate with the surface ocean, but the balance of the CO_2 exchange between the two compartments depends on the air–sea CO_2 concentration gradient, so for a more permanent removal from the atmosphere, the CO_2 carbon has to be transported further along the carbon cycle. For getting carbon transported away from the ocean and terrestrial biosphere by sedimentary burial, timescales are generally more than a thousand years, and for transporting the carbon even further down the carbon cycle, making it less likely to be re-emitted to the atmosphere, timescales get considerably longer.

Section 3.4 elaborates on the importance of the global carbon cycle timescales for the discussion of time horizons and accounting periods when crediting temporary carbon storage.

3.2 Temporary carbon storage impacts in the long time-perspective

Figure 2 shows the decay in time of the relative radiative forcing in the atmosphere from a CO_2 release, using Eq. (3). The figure illustrates a release at present, compensated by storage of an equivalent amount of biogenic carbon for 100 years, with an accounting period of 100 years, but using a 200-year time horizon (see Fig. 2a) and a 1,000-year time horizon (see Fig. 2b) from the present release. The time horizon starts counting at the time of every emission and implies a cutoff of the impacts from the 'tail' of an emission left after the time horizon, the accounting period starts counting from the time the carbon is stored and implies a cutoff of every impact occurring after the accounting period.

Figure 2a illustrates how storing carbon for 100 years before releasing it again pushes the entire cumulative impact of the emission (the area under the relative radiative forcing curve) beyond the PAS 2050 100-year accounting period. This means that when the biogenic carbon stored as compensation for the original fossil CO_2 emission is released after the 100-year accounting period, it is 'hidden' by the chosen accounting period. Figure 2b illustrates the modest effect the 100-year emission delay has, when seen in a long-term perspective.

This example presents the main problem with crediting temporary absence of the increased CO_2 levels in the atmosphere with permanent CO_2e credits; the inherent view of the credited emissions as avoided, thus disregarding the long-term impacts, which will be changed very little by the temporary storage.

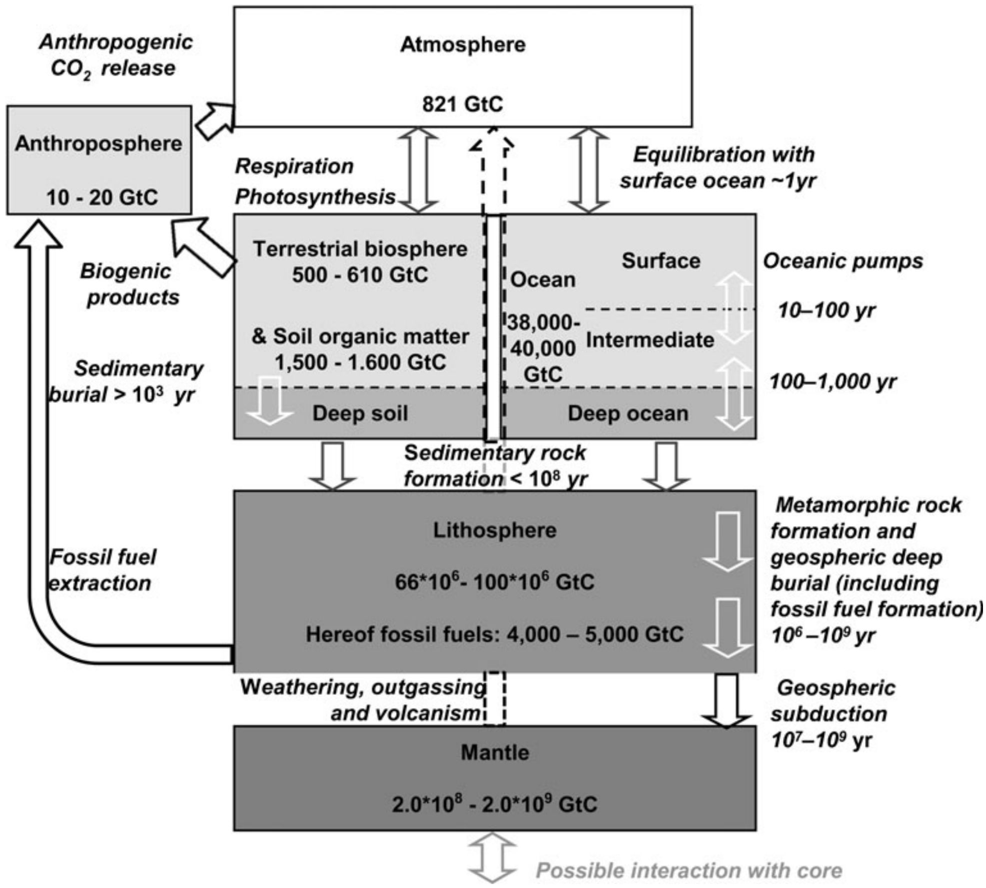

Fig. 1 Model of the global carbon cycle with carbon stocks, transport processes and indication of associated timescales (based on a literature study documented in the "Electronic supplementary material" together with underlying assumptions). The stock of the anthroposphere should be seen as a rough estimate extrapolated from various references. The uncertainty of the estimated carbon stocks and the timescales for exchange between the stocks generally increases with depth into Earth's interior

As illustrated by Fig. 2, the implication of using this approach is that storing e.g. 1 GtC in wooden products for 100 years neutralises the release of 1 GtC from combustion of fossil fuels. Taken to an extreme, this implies that there is no need to decarbonise electricity production. Using this assumption, fossil fuel burning can continue as long as an equivalent mass of carbon is stored in the form of wood or other biogenic carbon carriers for 100 years, provided that this carbon storage would not take place otherwise. The real output of such an endeavour would still be the total impact of the CO_2e of the fossil fuel reserves used in the electricity production, only delayed by 100 years.

3.3 Accounting period dependency of the PAS 2050 results

Figure 3 shows GWP saving factors, calculated for accounting periods from 2 to 1,000 years, using the approach of the PAS 2050 approximation for short delay times, Eq. (7), valid for carbon storage times of 2–25 years.

As seen from Fig. 3 the GWP saving factor for carbon storage for 2–25 years is highly dependent on the chosen accounting period. Results in Table 1 illustrate the influence of this time dependency on the GWP savings in a case involving storage of 1 GtC for a period of 20 years, using the PAS 2050 approach.

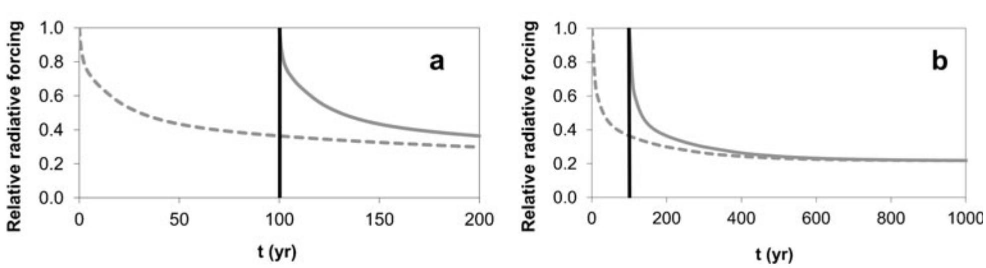

Fig. 2 Relative radiative forcing following a CO_2 emission (*punctuated grey line*) described by the CO_2 decay function given by IPCC (Eq. 3), but compensated by an equivalent amount of biogenic carbon being stored for 100 years. The cutoff of emissions occurring after the 100-year accounting period (*black vertical line*), means that the release of the stored carbon after 100 years (*full grey line*), is not counted. This is illustrated for two time horizons with respect to the present release: 200 years (**a**) and 1,000 years (**b**)

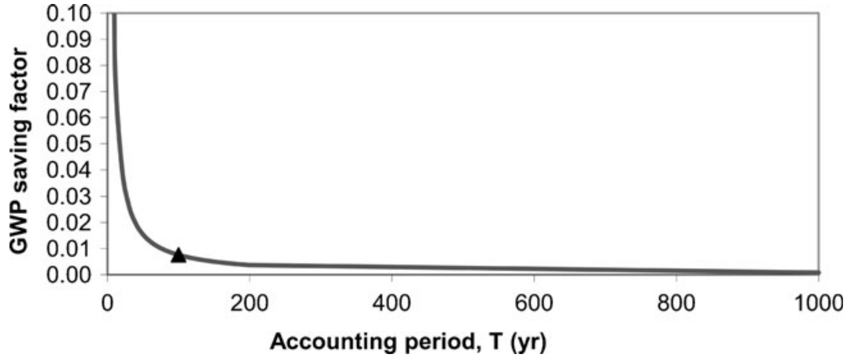

Fig. 3 GWP saving factor as a function of accounting period, based on the simplified approach given in Eq. (7) for storage times of 2–25 years as suggested by Clift and Brandão (2008). The *triangle marker* indicates the choice of the PAS 2050

Table 1 shows how the use of an accounting period of 200 years instead of 100 years reduces the credits of temporary carbon storage, for 2–25 years, to less than half, while deciding on a thousand year accounting period decreases the storage credits by almost a factor of 10. The time dependence of the GWP saving factor, and thus the crediting, for carbon storage for 2–25 years approaches an inversely proportional function, as illustrated by Fig. 3.

In the case of storage in longer periods or storage with a carbon leakage, the PAS 2050 weighting factor, Eq. (1), is simply inversely proportional to the length of the chosen accounting period and thus give similar results.

This shows that the choice of accounting period for the crediting is essential for the outcome, both for storage for 2–25 years and for longer storage times. The choice of accounting period should thus be considered carefully in order to obtain results that are meaningful in reflecting the climate change mitigation value of temporary carbon storage.

The issue of time horizon impacts on the value of temporary carbon storage has since submission of the present paper also been discussed in Levasseur et al. (2012).

3.4 Atmospheric CO_2 removal: reversibility and relevant time horizons for long-term effects

Some current proposals for crediting temporary storage of carbon are based on the argumentation that storing carbon for a certain time will compensate the cumulative radiative forcing of an equivalent CO_2 emission during the time it resides in the atmosphere, as outlined in Moura-Costa and Wilson (2000): During the applied accounting period, natural transport processes remove a part of the CO_2 emission from the atmosphere, meaning that the cumulative impact over the accounting period is lower than it would have been if the full amount of CO_2 had stayed there. A simultaneous storage of carbon on the other hand will contain the full amount of carbon for the whole storage period (provided no leaking). Thus it is argued that the time carbon needs to be stored to compensate the cumulative impact from the release of an equivalent amount of atmospheric CO_2 is significantly less than the accounting period (Moura-Costa and Wilson 2000).

Table 1 Carbon credits given for 20 years storage of 1 GtC with varying accounting periods between 100 and 1,000 years, using the GWP saving factors from Fig. 3

Accounting period, *T* (year)	GWP savings (tC)	GWP savings (tCO_2e)
100	0.152	0.557
200	0.0740	0.271
1,000	0.0162	0.0594

Results first presented by Jørgensen and Hauschild (2010) at an expert workshop on temporary carbon storage. Conclusions summarised in Brandão and Levasseur (2011)

Besides ignoring impacts after the accounting period, this argumentation ignores the fact that the uptake of CO_2 by the terrestrial biosphere and the ocean is based on reversible mechanisms that depend on the CO_2 concentration, and most of the stored CO_2 remains in those near-surface carbon reservoirs, while only small parts are moved more permanently by transport to more stable reservoirs in the carbon cycle (Denman et al. 2007) on much longer timescales as shown in Fig. 1. The near-surface storage is rather labile and liable to release the stored CO_2 again on quite short timescales as a response to changes that could occur as consequence of the increased atmospheric CO_2 concentrations, e.g. as temperature increase leads to a reduced solubility of CO_2 in the oceans. Another influential change could be that the removal of CO_2 from the atmosphere through mitigation measures to decrease the global warming potential, would cause a reduction in the air–sea CO_2 gradient. This again will reduce the uptake rate of CO_2 in the ocean (Kirschbaum 2006) and maybe even trigger release of some of the CO_2 already dissolved in the upper ocean layers, thus making the decrease in atmospheric radiation smaller and decreasing the climatic benefits.

Besides, the removal of atmospheric CO_2 is determined by the uptake rate into ocean and terrestrial biosphere, and it will change with e.g. the exhaustion of the ocean buffer effect due to man-made CO_2 emissions (Archer and Brovkin 2008), as well as decreased uptake capacity by

not only the ocean, but also the terrestrial biosphere, as a response to global warming (Denman et al. 2007).

Thus, the accounting period should reflect the timescales of removal of carbon to less labile carbon pools, e.g. further down the layers of Earth, rather than just transport to near-surface reservoirs, with the inherent risk of short-term re-emission to the atmosphere in response to changes in surface-related conditions. At least if the argument for crediting temporary carbon storage and allowing it to neutralise emissions of fossil carbon to the atmosphere is that the storage should compensate the total impact of a similar atmospheric amount of CO_2 within the accounting period.

3.5 The urgency issue

In the discussion of relevant carbon storage times for compensating climatic impacts of CO_2 emissions, the long-term implications is however not the only consideration. When considering the urgency of stopping the increased global warming before it passes a tipping point beyond which there may be no return (Meehl et al. 2007), even short-term storage may be of value. This points to political reasons for introducing a crediting system that also rewards storage solutions that only have short-term mitigation potential, as long as these are implemented at near-present time and thereby help addressing the urgency issue of keeping atmospheric CO_2 concentrations below such critical levels. If credited, it should be emphasised that the only merit in short-term storage solutions lies in their potential as bridging technologies, facilitating temporary solutions until more sustainable permanent solutions are available. It must be stressed that short-term storage does not solve the problem of the long-term presence of too high atmospheric CO_2 levels.

4 Conclusions

In this light, the optimal way of achieving climate change mitigation potential from temporary carbon storage in carbon footprinting could be a dual approach that considers both the long-term persistence issue regarding increased CO_2 levels in the atmosphere and the concern of tipping points. Thus generally, carbon storage should be credited as negative CO_2e in the carbon footprint account only if meeting the long-term requirements of storage of at least thousands of years. Some carbon capture and storage (CCS) options may have the potential to meet this requirement, as it is assessed that if kept in properly chosen and managed reservoirs, it is likely that the part stored after 1,000 years will still be more than 99 % (Rubin et al. 2005).

For the short-term storage with bridging potential, another type of carbon credits could be introduced, thus offering incentives for those but not interfering with the long-term carbon footprint account. The development of such an incentive system is however beyond the scope of this paper. One existing suggestion for including the urgency issue in climate change impact assessment in general, which could be applied to the issue of temporary carbon storage, is the global temperature potential metric, which considers the relative temperature impact of GHG emissions in relation to the proximity to a climatic target level (Shine et al. 2007). Another option could perhaps be to use an existing suggestion for temporary carbon storage crediting, such as the PAS 2050 discussed here, but give it its own category, not interfering with the general carbon footprint, as currently suggested. For the latter, this has the limitation that it does not address the increasing urgency issue. However none of those options are considered fitting for addressing the complete aspects of the climatic urgency issue in relation to value of temporary carbon storage. Thus, further work in this area is recommended. For both long-term and short-term storage, transparent reporting and control methods are necessary to ensure that storage is kept for the given timescales, and if not, that obtained credits are returned.

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